Load-Extension Diagrams taken with the Optical Load-Extension Indicator.

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[Plates 2 and 3.]

This paper may be regarded as a continuation of that communicated in January, 1912,* wherein I described a new optical apparatus by means of which it is possible to obtain load-extension diagrams free from the inertia effects of the parts of the testing machine in which the materials are strained and broken.

The apparatus is automatic in its action and gives a true record of the physical properties of the materials. The curve corresponding to the straining and breaking of a specimen is drawn by means of a spot of light moving over a photographic plate placed in the camera which forms part of the instrument. There is no practical limit to the speed at which a diagram can be taken other than that imposed by the "rapidity" of the plate.

When fracture of a specimen takes place, the spot moves across the plate so rapidly that no impression is made, and hence the actual load carried by the specimen at the instant of fracture is determined without ambiguity, because the spot of light ceases to record at the instant of fracture. Even if a plate were used so rapid that the quick movement of the spot across the plate after fracture of the specimen were brought out, the discontinuity in the curve and the difference in intensity would fix the point accurately.

This property of the instrument, namely, its power of recording the true load-extension curve at any speed of loading, opens up a new field of research in the subject of the strength of materials, as is indicated below by the results obtained by the almost instantaneous straining of a piece of mild steel beyond its elastic limit.

The diagrams given in my previous paper related to mild steel, iron, and copper. The present paper relates to the physical properties of gun-metal, brass, and phosphor-bronze, as disclosed by their respective load-extension diagrams and the corresponding micro-photographs of their molecular structure; to further experiments on mild steel, with the instrument arranged somewhat differently in order to magnify the extension so much that the photographic record exhibits the elastic part of the diagram; and

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also to diagrams obtained by the application of load so quickly that the straining of the material up to the elastic limit may almost be regarded as done by an impulsive load.

Group 1.—*Copper-Tin and Copper-Zinc Alloys.*

A piece of *phosphor-bronze* which was turned to a diameter of 0·54 inch was broken in the testing machine by a load applied so that the rate of straining was approximately constant. The composition of the specimen was:—Copper, 89·7 per cent.; tin, 8·85 per cent.; lead, 1·21 per cent.; phosphorus, a trace.

The load-extension diagram is shown in fig. 1, together with the microphotograph showing the structure of the material. The magnification is 1500 diameters. (See Plate 2.)

The form of this diagram is in marked contrast to the form obtained from mild steel. There is no period of molecular instability between the breaking-down point and the plastic yielding, as in the case of mild steel. The curve is smooth and continuous from the commencement of the loading to the point of fracture. There is a quasi-elastic stretching of the material up to a load of about 7 tons, followed by a plastic yielding with a continually falling load.

Reckoned on the original area of the bar, the load at fracture corresponds to a stress of 22·9 tons per square inch. The reduction of area at the point of fracture was, however, 69 per cent. of the original area of the bar, so that the actual load carried by the bar at the instant of fracture was 74 tons per square inch. The extension of the bar measured on a gauge length of 5 inches was 9·4 per cent.

The peculiar scythe-shaped diagram of this material is different in almost every respect from the characteristic diagrams obtained from iron and steel.

Gun-Metal.—A load-extension diagram from a specimen of gun-metal is shown in fig. 3 and the corresponding microphotograph in fig. 4; magnification, 750 diameters; diameter of specimen, 0·6 inch; distance between the gauge points, 5 inches. The composition of the metal was:—Copper, 85·4 per cent.; tin, 12·4 per cent.; lead, 2·41 per cent.

There is a general resemblance in form between the curves in figs. 3 and 1, but the gun-metal has a considerably increased plastic limb. The quasi-elastic line in each diagram is very much the same in character, but the difference between the maximum load and the breaking load is not so great in the gun-metal as in the phosphor-bronze specimen.

The stress on the gun-metal specimen at the instant of fracture, reckoned on the original area of the bar, was 21·2 tons per square inch, but reckoned

on the actual area corresponding to a reduction of area of 55 per cent., it was 45·8 tons per square inch, considerably lower than in the case of phosphor-bronze. On the other hand the extension on 5 inches was 14 per cent., considerably greater than in the extension of phosphor-bronze. It is noteworthy that a not very great difference in chemical composition of the two materials results in a considerable difference in the physical properties.

Brass.—The load-extension diagram of a piece of brass rod is shown in fig. 5, and the corresponding microphotograph in fig. 6. Fig. 7 shows the load-extension diagram of a second specimen cut from the same brass rod, and fig. 8 shows the corresponding microphotograph. The magnification in both figs. 6 and 8 is the same, namely, 190 diameters. The first specimen (fig. 5) was tested just as it was cut from the rod. The second specimen (fig. 7) was annealed in a muffle furnace before testing. The specimen was heated to a dull red, and then allowed to cool in the furnace, the cooling lasting about four hours. (See Plate 3.)

Comparing the two load-extension diagrams together and also the two corresponding microphotographs together, it will be seen that the process of annealing has exerted a marked influence on the physical properties and on the molecular structure of the material. In fact, the annealing process has destroyed entirely the quasi-elastic part of the load-extension diagram. Whereas the unannealed bar carried a load of nearly 7 tons before passing into the plastic state, the annealed bar begins to approach that state before a load of 2 tons is reached. Further, if the diagram for the annealed bar is compared with the load-extension curve of the copper bar given in my previous paper it will be seen that there is a striking resemblance in form. The resemblance is so close that at a first glance the load-extension diagram of the annealed brass bar would be mistaken for a diagram from a copper bar. The composition of the bar is as follows:—Copper, 58·6 per cent.; zinc, 40·8 per cent.; lead, 0·6 per cent.

There is a marked contrast also in the crystalline structure. In the unannealed state (fig. 6) the metal appears to be constructed of two kinds of material, roughly equal in size and uniformly distributed; the lighter areas represent one kind of crystal, and the darker areas another kind. After annealing (fig. 8), it will be observed, the dark areas have grown and the lighter areas have almost disappeared. The magnification is the same in each figure, hence it is clear that the substance represented by the darker area has grown into aggregates of relatively large size. These large aggregates seem to indicate that the long period of annealing has probably resulted in the formation of a true eutectic alloy.

Another peculiar characteristic of brass will be seen on the diagrams for both the annealed and the unannealed specimen, namely, the peculiar discontinuities in the curve as the specimen draws out. These discontinuities appear earlier on the diagram of the unannealed specimen than on that of the annealed specimen. The bar itself gives evidence that the internal stress has been somewhat differently distributed than in the case of the other metals tested, because after it has been drawn out to a length approaching the breaking-point the bar is no longer round but veined. To the hand it feels as though the original smooth, circular, and apparently homogeneous bar has been drawn out into a bundle of thick strings.

The effect of annealing is also shown by comparing the ultimate stress and elongation of the specimens, though the annealed specimen extended so much that the end of the curve did not appear on the plate; consequently the actual load at fracture could not be measured.

	Unannealed.	Annealed.
Percentage elongation on 5 inches	20·0	42·4
Percentage reduction of area..........................	18·8	46·0
Maximum load per square inch carried by the bar, reckoned on the original area	29·2	25·7 tons.
Load per square inch carried by the bar, reckoned on the actual area at fracture	42·8	

A common characteristic of all the alloys tested was the absence of a true elastic modulus. The load line begins to bend away very soon after extension begins.

Mild Steel Specimen Broken with Suddenly Applied Load.

One of the most interesting diagrams I have ever taken with the apparatus is that shown in fig. 9. A mild steel specimen was put with the apparatus into the shackles of a 30-ton testing machine. The straining cylinder of the machine was connected directly to the hydraulic main of the works. The accumulators were pumped to the top of their strokes, and the pumps were then stopped. The regulating valve on the testing machine admitting water to the straining cylinder was then opened wide, as quickly as it was possible to turn it, with the result that the whole break occupied only 10 seconds. Notwithstanding this extremely rapid break, the whole of the load-extension diagram was obtained with the apparatus, with the exception of just the end, which came off the plate. Everything worked perfectly, and after the fracture the spot of light came back to its initial position.

Although the whole period of the break was small, namely 10 seconds,

the time occupied by the purely elastic extension was a very small fraction of the whole time. This is indicated by the relative intensity of the line in the elastic and in the plastic part of the diagram in the actual photograph. The time occupied by the elastic extension was certainly less than 1/10 second.

Fig. 10 is placed beside fig. 9 for the purpose of comparison. The curve is the load-extension diagram of a second specimen cut from the same bar as that from which the specimen broken in 10 seconds was cut, the load-extension diagram of which is shown in fig. 9. The time occupied in breaking this second bar was $2\frac{1}{2}$ minutes. The effect of the rapidity of the straining on the apparent properties of the material can be estimated by a comparison of the two figures.

Each bar was 0·55 inch diameter, and in each case the gauge points were 5 inches apart. The scale of extension is practically the same in each case, namely, $3\frac{3}{4}$ to 1, whilst the load scale is just the same, and is practically 1 ton = 9 mm. on the original diagrams.

The following results are found by measurement from the diagrams and the bars.

	10-second break (fig. 9).	150-second break (fig. 10).
Original diameter	0 ·55 in.	0 ·55 in.
Original area	0 ·238 sq. in.	0 ·238 sq. in.
Fractured area	0 ·071 „	0 ·084 „
Reduction of area	70 per cent.	65 per cent.
Gauge length	5 in.	5 in.
Extension	1 ·45 in.	1 ·22 in.
Elongation	29 per cent.	24 ·4 per cent.
Maximum load reckoned on the original area of the bar	26 ·5 tons per sq. in.	25 ·2 tons per sq. in.
Load at yield point	25 ·2 „ „	24 ·0 „ „

Comparing these results, it will be seen that the rapidity of breaking has little effect on either the yield-point or the maximum loads, but has a more marked effect on the plastic properties of the material. With quick loading the extension of the material on 5 inches increases from 24 to 29 per cent., and the reduction of area is increased from 65 to 70 per cent.

A third specimen cut from the same bar was broken in 9 seconds, and the curve obtained was essentially the same as that shown in fig. 9.

Load-Extension Diagrams of the Elastic Part of the Curve.

A specially designed extensometer and a modified arrangement of the instrument were used to obtain a diagram of just the elastic part of the

curve. Fig. 11 shows a diagram taken from a piece of mild steel in which the extension is so magnified by the instrument that only 0·01 inch extension appears on the diagram. The scale of extension is such that 2·1 inches on the diagram represents an actual extension of 0·01 inch of the specimen. By measurement of this diagram it was found that the bar extended 0·0804 inch on 5 inches for a change of load of 6 tons, the area of the bar being 0·282 square inch. From these data $E = 13{,}240$.

A similar diagram is shown in fig. 12 for a piece of electrolytic copper. From this it appears that copper has no true modulus of elasticity, since it begins to curve away directly the load is applied. It would almost appear that for materials of this kind another definition of the modulus of elasticity should be used, if the term is used at all. For example, it might be defined as the ratio between unit stress and unit strain measured from a tangent at the origin of the diagram.

The difficulty of taking diagrams with this great magnification of the extension is chiefly that, with the ordinary testing appliances, it is difficult to get a true axial pull on the specimen. For this kind of work it is necessary to use the device of crossed knife-edges instead of the ordinary spherical joints usually found in testing machines.

The diagrams shown in this and the preceding paper sufficiently illustrate the use of the apparatus as an instrument of research in determining the strength of materials, and indicate that many lines of investigation may be followed in connection with the determination of the physical properties of materials.

Summarising the points of advance made :—

(1) The diagrams are obtained free from inertia of the heavy mass of the beam of the testing machine and the jockey weight usually used as part of an autographic recording apparatus.

(2) Pencil friction is entirely eliminated, since the diagram is obtained by the movement of a spot of light over a photograph plate, the movement of the spot being determined by small angular displacements of small light mirrors.

(3) The load on the specimen is measured by a weigh-bar placed in series with it. A variation of 1 ton on the specimen causes an elongation of about 0·001 inch on the weigh-bar. This movement is multiplied by the mirror and beam of light to a movement of about 1 cm. on the photographic plate.

(4) An extensometer is placed on the bar to measure its extension, and up to the elastic limit the specimen extends a distance of the order 0·01 inch on a 5-inch length. This movement is multiplied by a mirror and beam of light to about 4 cm. on the photographic plate.

(5) The accuracy of the multiplication and the sensitiveness of the mirror

gear and extensometer are shown by the results obtained in fig. 11. Fig. 11 may be regarded as a refined test of the instrument, since the slightest deviation from true proportionality in the multiplying mechanism of the instrument would be apparent on the elastic curve of a piece of mild steel. As shown on the diagram, the line is straight and has a slope which gives an elastic modulus known to be correct from independent measurements.

The accuracy of the instrument being established by this test, the accuracy of the curve in fig. 12 for copper, which was obtained by the instrument, is also established.

(6) The accuracy with which the instrument will follow the quick variations of stress in the specimen, that is to say, the freedom of the apparatus from lag due to inertia of the parts, is indicated by the diagram fig. 9, which shows how every detail of the variation of load and corresponding extension is brought out, even when the loading is so rapid that it is almost impulsive. The elastic part of the curve in this figure was described in certainly less than 0·1 second. From other evidence I know that the instrument will follow quicker variations than this, the first limit to the speed being the speed of the plate.

(7) The elastic line is drawn by the instrument continuously without a stop. An elastic line plotted from observations in the usual way is drawn through points which correspond to periods of dead loading. The loading is, in fact, intermittent, a stop being necessary at each load added to measure with an extensometer the elongation produced by the load.

(8) In the diagrams of the whole curve up to the break, as in fig. 10, the load on the bar at the instant of fracture is recorded.

Comparison of the Physical Characteristics of the Materials Tested.

When compared together the diagrams of gun-metal, brass, phosphor-bronze, copper, steel, and iron show two distinct parts: the elastic or quasi-elastic part, and the plastic part. There is, however, a sharp distinction between the alloys of copper, tin, and zinc and irons and steels. The distinction lies in the manner in which the material passes from the elastic into the plastic state. In the case of pure copper and its alloys, it is impossible to say where the elastic state ends and the plastic state begins. The elastic diagrams of the alloys of copper, tin, and zinc all show a quasi-elastic line (a line which in fact may almost be mistaken for an elastic line in those diagrams which show the whole of the break) with a perfectly smooth join on to the plastic part.

With the iron and steels, the elastic part of the diagram ends not quite suddenly but with a quick change into a curve where there appears to be

some struggle going on in the bar between the broken crystals, a struggle which apparently is settled, after an extension of about 0·1 inch, in favour of a predominating plastic partner. The curves obtained from annealed and unannealed brass rod, when considered with the micro-photographs and the curve from pure copper, show that the plastic properties of the materials are profoundly modified by the size of the aggregates from which the material is built up. And if steel is assumed to be an alloy of iron constructed of iron aggregates of large size through which is distributed a network of crystalline structure, the peculiar characteristic diagram which is always obtained from steel may be explained on the assumption that it is the resultant load-extension diagram of two separate materials, the one material being present as a hard crystalline structure, the other being the iron with which it is associated. The material breaks down in the elastic sense when this crystalline network gives way, but it continues yielding in the plastic sense and even carries a greater load than was carried at the time the network failed before local yielding begins. The giving way of the crystalline network is probably only a slip of the crystals, because, as is well known, annealing in boiling water appears to restore the elastic properties of the bar, though this boiling does not cause the bar to return to its original length, it merely permits the reconstitution of the network into a resisting system in the new relative position of the crystals produced by the first slip. It would be interesting to obtain the diagram of a piece of chemically pure iron. The load-extension diagram would probably be the same in character as that of pure copper.

I should like finally to express my thanks to Mr. W. H. Merrett, of the Royal School of Mines, for making the micro-photographs which are used to illustrate the paper.

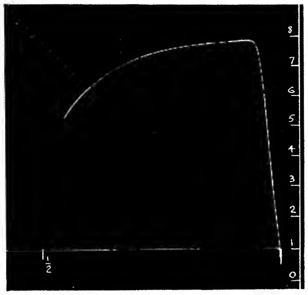

FIG. 1.

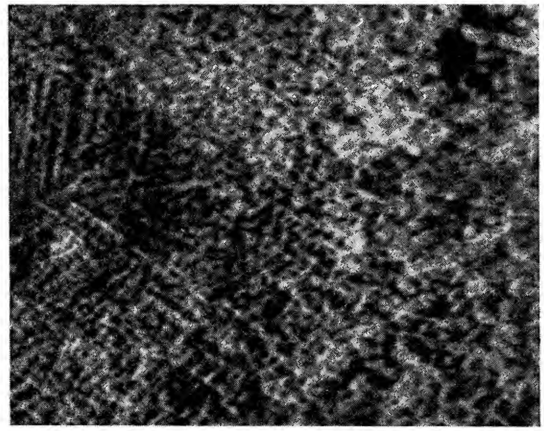

FIG. 2.

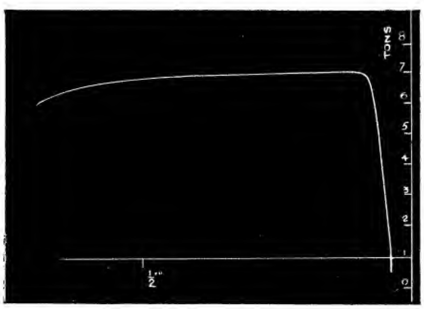

FIG. 3.

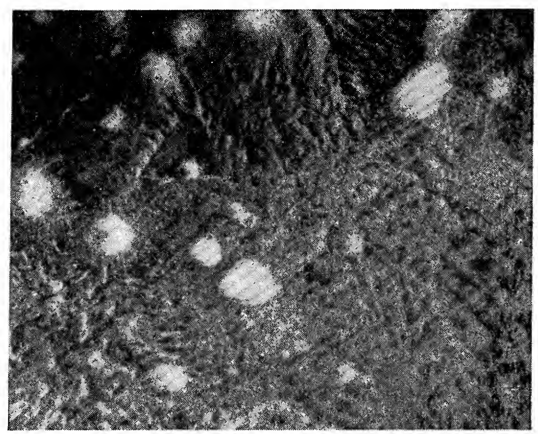

FIG. 4.

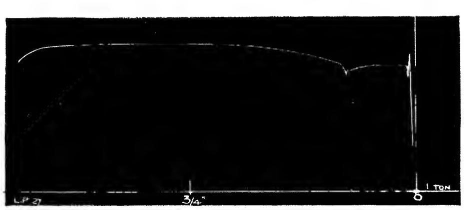

FIG. 9.

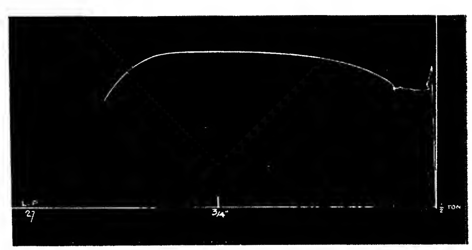

FIG. 10.

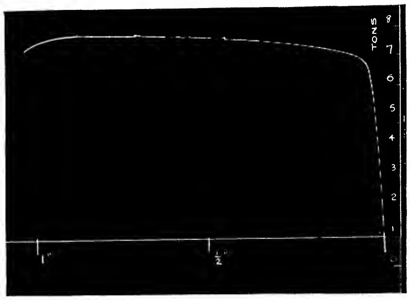

FIG. 5.

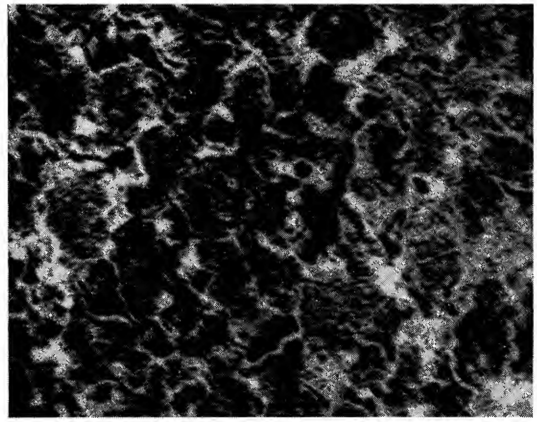

FIG. 6.

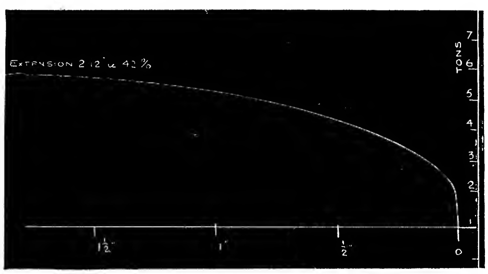

FIG. 7.

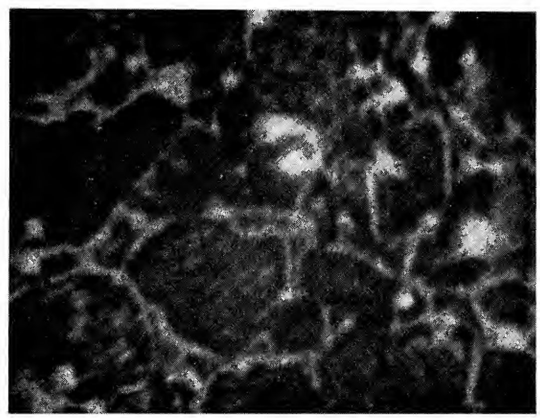

FIG. 8.

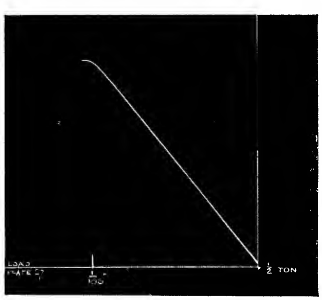

FIG. 11.

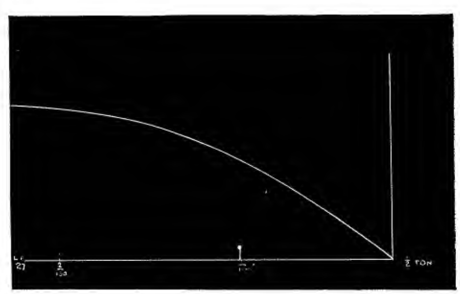

FIG. 12.

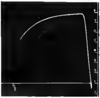

FIG. 1.

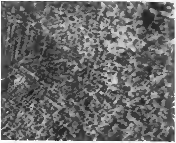

FIG. 2.

FIG. 3.

FIG. 4.

FIG. 9.

FIG. 10.

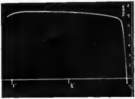

Fig. 5.

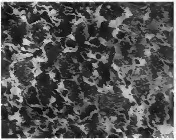

Fig. 6.

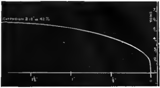

Fig. 7.

Fig. 8.

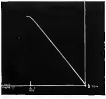

Fig. 11.

Fig. 12.